Advanced technology

Welcome to the mirror world

Digital twins are fast becoming part of everyday life

WHEN VISITING a doctor a few years from now, you can expect to be accompanied by a virtual version of yourself. This so-called digital twin will be a working model of your body that can be summoned onto a physician's computer screen. Updated with your latest vital signs, it will help the doctor make an accurate diagnosis. It also opens the door for medicines and procedures designed specifically for you, greatly increasing recovery rates.

This might seem like fantasy, but the foundations are being laid. Researchers at Queen Mary University of London already use computer simulations of the hearts of individual patients to evaluate different treatments for atrial fibrillation, a common disorder. It would be far too risky to experiment this way on someone's real heart. With other organs also being twinned by scientists, it seems likely they will eventually link up to form a virtual body.

As our Science & technology section reports, digital twins are starting to pop up everywhere. Among other things, they monitor the health of jet engines on airliners, keep track of Uber's network of vehicles and replicate Amazon's extensive supply chain well enough for the online retailer to accurately forecast sales several years ahead. They are helping local authorities respond to the effects of flooding and letting carmakers shave years off the development of new models by simulating test drives and crashes. Twins are also being developed to help manage factories, companies and entire cities. All this is being turbo-charged by recent progress in artificial intelligence (AI), which gives twins the ability to make predictions about their physical counterparts, and fine-tune themselves on new data.

Digital twins began as basic computer models of physical objects and systems. As computers have become more powerful, twins have become more sophisticated. Complex design and modelling software means many physical objects initially take shape in the virtual world. Small sensors, capable of measuring all sorts of things, feed twins with real-time data, ensuring that they mirror their physical counterparts. A Formula 1 racing car, for instance, may have more than 250 sensors updating its digital twin during a grand prix.

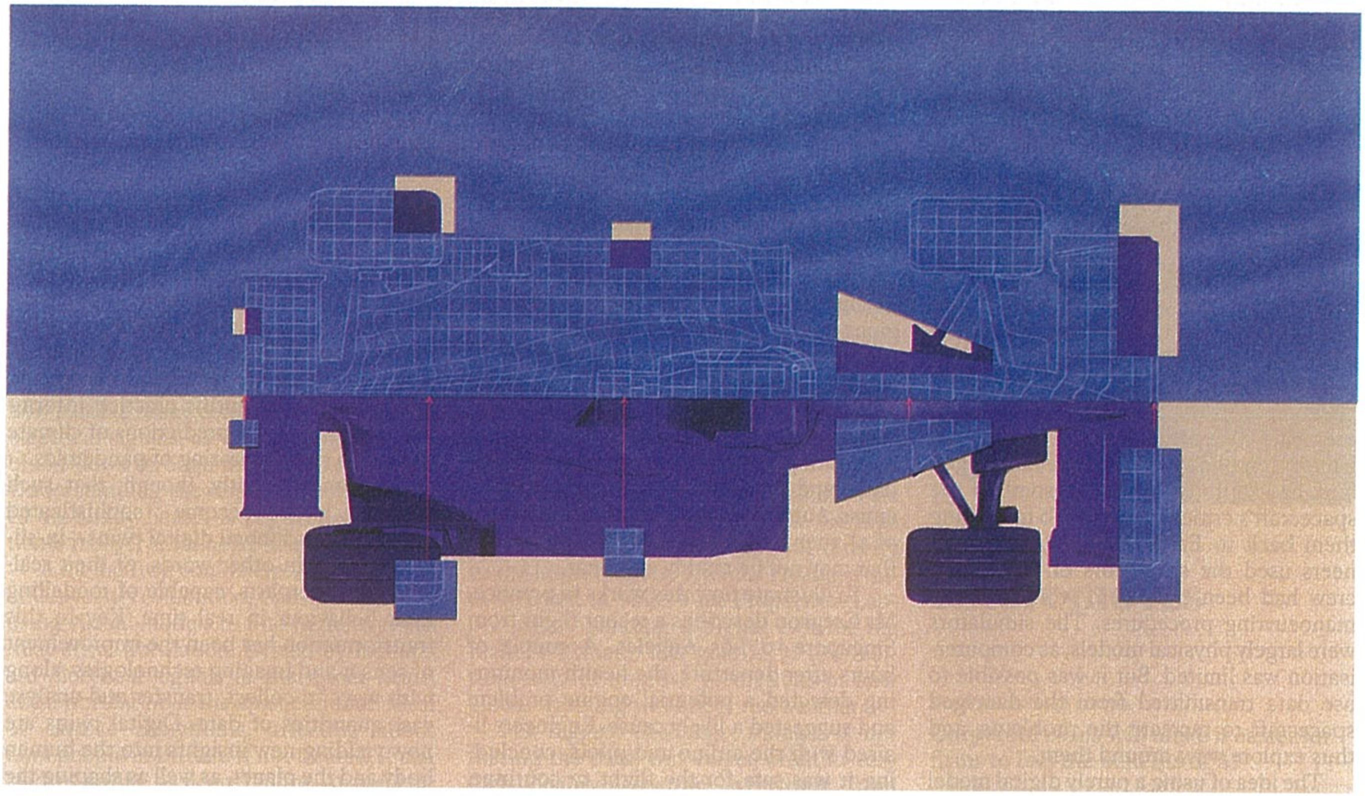
The use of AI takes all this much further, allowing virtual models to become more sophisticated, and to both simulate and optimise activities in the real world. You may worry that this portends a dystopian future; Morpheus, a character in a science-fiction film from 1999 in which a sentient machine subdues humanity through pervasive virtual reality, had a name for it. As he said: "The Matrix is everywhere. It is all around us."

Reality is more prosaic. The idea of creating symbolic representations of real-world things is centuries old. Many ancient civilisations built architectural models, sometimes to place into tombs but also to work out how to build things. Double-entry book-keeping, developed in the 15th century, was a paper-based representation of a merchant's finances. The Phillips Machine, a hydraulic computer from the 1940s, created a physical "twin" of national economic flows. Spreadsheets and supply-chain management systems enable companies to log transactions, track inventory, make forecasts and model future scenarios.

Today's digital twins extend this process, making it easier for humans to tackle complex problems. They can act as virtual crystal balls, allowing people to peer into the future, spot problems before they materialise and test wild ideas without real-world consequences. For businesses, this should mean better designs, more streamlined operations and fewer costly blunders. For society, the promise is equally tantalising: personalised health care, cities that flow and breathe more easily and, thanks to the threats exposed by climate modelling, clues as to how the planet might avoid environmental catastrophe. Digital twins offer the ultimate sandbox in which castles can be built and tested before being made real.

Could these virtual doppelgangers go rogue? They might if they are programmed badly, or hacked into. Avoidable medical conditions could be ignored, corporate systems sent awry and critical power plants compromised. Digital twins will gobble up mountains of data, some of it wrong, some of it prejudiced and much of it raising concerns about privacy and surveillance. There is also the danger of tunnel vision as humans rely more and more on digital twins—and miss things that sensors might not be able to capture. Yet these risks are not specific to digital twins. They apply to all emerging technologies, as they always have and always will. Such concerns need to be considered, as in the current debate over the use of AI. The emergence of the digital mirror world will doubtless raise new questions, but its potential advantages are already plain to see. ■

Science & technology



Digital twins (1)

Off to the races

MILTON KEYNES

This special section explores the use of digital twins in fields ranging from health care to industry. First, how they are speeding up manufacturing

When a factory has secrets to protect it is not unusual for security staff to ask that no photos be taken. This industrial campus in Milton Keynes, north-west of London, however, is particularly cautious. It is the home of Oracle Red Bull Racing, a Formula 1 team involved in a competitive contest that relies on levels of engineering so advanced they would leave most manufacturers in the dust.

Red Bull employs some 1,500 people building racing cars. Their principal mission is to keep two of those cars at the peak of their performance for the team's drivers—Max Verstappen (the winner of three world championships since 2021) and Sergio Pérez—to deliver more race victories during the 2024 Grand Prix. Out on the track, they race in a world where mere fractions of a second over a minimum of 305km separates winners from losers. But there is another world in which the F1 teams battle it out: a virtual one.

During a season Red Bull's cars will be subject to several thousand design changes and tweaks. These have to be done at breakneck speed, with components designed, tested, shipped and fitted in a matter of days between races. There is no room for error. Like its F1 rivals, the only way Red Bull can maintain such a pace is by using software that simulates the entire production process, so that any problems are ironed out before they emerge. That simulation is done using what is called a "digital twin". The advantages such twins offer in speed, reliability and cost together represent the future of manufacturing.

A digital twin is a virtual representation of something. It could be an object, like a car or an aircraft. Or, as we consider in the next two stories, it could be more complex systems, such as industrial processes or bodily organs. Even in the case of a humble car part, it encompasses more than physical attributes, from details about how the object was built and how it ages to how it breaks and the way it can be recycled.

To work, a digital twin needs to be constantly updated by its physical counterpart. This is done using real-time information gleaned from sensors that measure just about anything that can be measured. In the case of Red Bull, each of its cars' digital twins is updated by more than 250 sensors constantly checking things like engine performance, tyre temperatures and suspension movements. By the end of a race, the amount of wireless data relayed by each car back to a team's engineers can be in the terabytes.

The race track serves as a laboratory for the transfer of digital twins to the broader motor industry, says Ignazio Dentici, head of the automotive division of Hexagon, a Swedish company which supplies twinning technology. This includes laser scanners, which Red Bull uses to check the dimensions of components down to an accuracy of two millionths of a metre. That might seem extreme, but F1 is an extreme sport. Not only does such accuracy ensure that parts match the design specs, it also ensures that they do not stray outside the strict dimensions laid down by F1 rules, which can lead to disqualification. ▸▸

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The digitisation of car design and the virtual testing of prototype vehicles in a simulator has helped shrink the process of taking a new model of a regular vehicle from conception to mass production from around five years to about two, adds Mr Dentici. Carmakers are now trying to create digital twins of their factories and supply chains to plan production more efficiently. As the volume of data grows, artificial intelligence (AI) will help analyse the twins and suggest improvements.

Surprise! It's twins

All this is a long way from where digital twins began. That is usually pegged to the Apollo space programme and, in particular, April 13th 1970. On that day the (often misquoted) words "Houston, we've had a problem," were uttered, as the three astronauts on Apollo 13 reported that an oxygen tank had ruptured, disabling some of the spacecraft's critical systems. To help bring them back to Earth safely, NASA's engineers used the simulators on which the crew had been trained to work out new manoeuvring procedures. The simulators were largely physical models, as computerisation was limited. But it was possible to use data transmitted from the damaged spacecraft to recreate the problems, and thus explore ways around them.

The idea of using a purely digital model for engineering spread as computer power increased and sophisticated design and manufacturing programs emerged. Specialised software has also been developed for things like structural analysis and computational fluid dynamics, which can be used to explore aerodynamics without the need for an expensive wind tunnel. At the same time, powerful computer graphics allow results to be displayed in more elaborate ways, including virtual-reality systems that let engineers peer inside things like aircraft wings, as well as driving virtual cars on virtual roads and race tracks.

These tools are now being used on the grandest scales. At the Tinker Air Force Base in Oklahoma, all 76 of America's fleet of giant B-52 bombers need their engines replaced. These cold-war aircraft date from the 1950s and each has eight jet engines, configured as pairs of jets contained in four pods, hanging under their wings. The work, and the way the updated bombers will fly, is already well understood. This is because the entire process has been extensively explored using a digital twin.

When the engine-replacement programme was put out to tender, the US Air Force made digital models a requirement, ruling out any paper plans. This virtual "fly-off", potentially worth $2.6bn, was won by Rolls-Royce, a British engineering group, using a digital twin that replicated its F130 military engines installed in a B-52. These engines will be manufactured at a Rolls-Royce factory in Indianapolis.

Rolls-Royce, along with its two big American rivals, General Electric and Pratt & Whitney, which also competed for the contract, were among the first to start using digital twins to monitor the performance of their engines. Airlines used to buy engines for their aircraft, maintain them and carry their own stock of spares. Now they mostly rent their engines using a subscription model known as "power by the hour", which means manufacturers are paid only when their engines are working.

As a result, "we are heavily incentivised to understand how our fleets of civil engines are behaving," explains Steve Gregson, a senior Rolls-Royce engineer. Each engine, therefore, has a digital twin. Whenever the real engines are airborne, sensors relay data to an open-all-hours monitoring centre where the twins are updated and checked for anything that looks amiss. Automated algorithms, using a form of AI, then look for patterns and anomalies that may not be readily apparent.

To illustrate how this works in practice, Mr Gregson describes a recent flight from Singapore to Los Angeles. A couple of hours after departure, the health monitoring detected a potential engine problem and suggested a likely cause. Engineers liaised with the airline and pilots, concluding it was safe for the flight to continue. Meanwhile, a team of technicians were summoned from Indianapolis, spare parts were put on a plane from France, and a replacement engine sourced. By the time the flight landed, a team was ready to make repairs and get the aircraft back into the air as quickly as possible.

Spotting problems before they occur has both safety and financial benefits. It also makes routine servicing more effective. Aircraft used to require their engines be serviced at set intervals, even though some journeys cause more wear and tear than others. Planes flying out of an airport in a desert region, like the Middle East, can ingest gritty dust particles, which abrade components faster. Certain flights are more heavily laden, which adds stress. And some pilots push the throttles harder than others. As the digital twin takes such things into account, maintenance schedules can be tailored to how each engine is actually wearing. This means some engines can stay on the wing as much as 30% longer, says Rob Fox, a senior design manager with Rolls-Royce.

Although many cars inform their owners when they need servicing, most do not have sophisticated digital twins keeping tabs on them the way jet engines and F1 cars do. But as sensors get cheaper and model-building becomes easier, that could change. Other products may follow, from phones to washing machines. The technology is yet to enter its highest gear. ■

Digital twins (2)

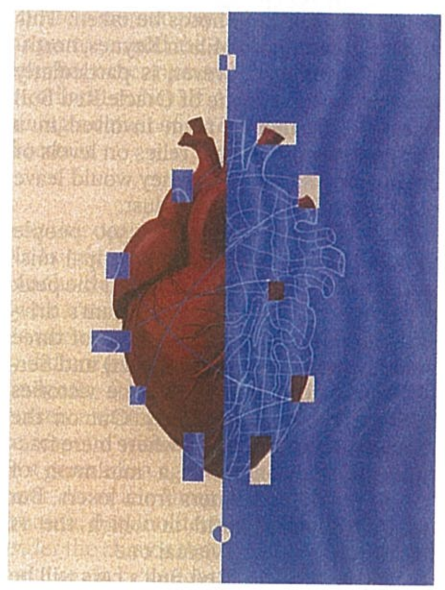
The heart of the matter

Scientists hope to simulate everything from human organs to the planet itself

SCIENTISTS ARE no strangers to computer models. Some of the very first uses of computers to simulate reality, in fact, were built by physicists keen to understand the behaviour of subatomic particles, and meteorologists hoping to predict the weather. Over the 75 or so intervening years, computer modelling has become an integral part of scientific practice, informing everything from predictions of climate change to the monitoring of pandemics.

It is only recently, though, that such models have become sophisticated enough to be dubbed digital twins—in-silico replicas, in other words, of their real-world counterparts, capable of modelling their behaviour in real time. Key to this transformation has been the improvement of sensor and imaging technologies, along with ways to collect, transfer and analyse vast quantities of data. Digital twins are now yielding new insights into the human body and the planet, as well as shaping the design of cutting-edge experiments.

Nowhere is this transformation more obvious than in health care, a field where digital twins have "exploded" in recent years, says Michelle Oyen, a health engineer at Washington University in St Louis. She attributes much of that growth to the drive towards personalised medicine. If an individual can have an entire organ reliably simulated, goes the thinking, then the effects of a disease and the likely impact of drugs can also be modelled in detail. ▸▸



Dr Oyen herself uses the technique to model the development of the placenta during pregnancy, and how that can influence the risk of stillbirth. Similar efforts are under way for other organs, including the lungs and kidneys. Researchers have even made progress on simulating the complex interconnections of neurons within the human brain, in order to model and study epileptic seizures.

The organ most relevant to engineers, though, is the heart, a system of valves and chambers that squeeze and relax up to a hundred times a minute to send blood around the body. And whereas hearts all follow the same laws of physics, each does so in different ways. Everything from diet and lifestyle to age and physique can alter how cardiac tissue contracts in response to electrical signals, as well as how smoothly blood flows through the heart's chambers. Understanding the impact of such changes on bodily health is key to helping patients recover from heart disease.

A digital twin could help. At Queen Mary University of London, Caroline Roney is using virtual models to find better ways to treat atrial fibrillation. Driven by haphazard electrical signals in the upper heart, atrial fibrillation is the most common form of cardiac arrhythmia, affecting about 1.4m people in Britain. If not treated, it can lead to stroke or heart failure. At present, that treatment often involves ablation: heating or freezing small diseased regions of the heart to form tiny scars that block errant electrical signals.

Patients respond to ablation in widely different ways, in large part, says Dr Roney, because of differences in cardiac tissue. She is, therefore, working to customise treatment, using digital twins to recreate the particulars of individual hearts and predict how they will react to ablation.

The first step is to make such a twin. Thanks to advances in scanning technology, the structure and composition of the heart can be replicated to within less than a millimetre. Crucially, such a computer simulation can also be programmed to replicate patterns of electrical conductivity in different regions of the heart, using information obtained from electrocardiograms (ECGs). By recreating these patterns in the modelled heart, the digital twin can be used to simulate ablation, as well as the probable patient response, before any surgery occurs. What's more, such digital twins could theoretically predict changes in the heart structure brought on by age, without the need for further scans.

And, in principle, twins of different organs can be developed separately and then combined, with the outputs from one used as inputs to the others. Dr Roney is part of a European consortium called the Ecosystem for Digital Twins in Healthcare, which works on ways to integrate twins of different organs, with the ultimate goal of creating a virtual human body. This would allow for more reliable modelling of everything from the effects of medication to the consequences of surgery. The project is due to publish a plan in September that sets out how exactly this could be achieved.

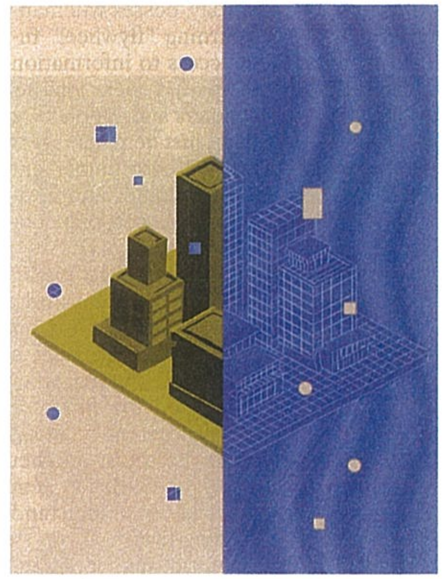
Some researchers dream of doing something similar with Earth, by combining digital twins of specific planetary processes. This would have real-world benefits. Thomas Coulthard, a physical geographer at the University of Hull, is building a digital twin of the local area to help authorities respond to heavy rainfall and storms. By modelling what happens to surface water when sluice gates and barriers are opened and closed, the twin lets everyone from water companies to individual landowners test the possible consequences of action and inaction.

Threading millions of such small-scale systems into a global patchwork will take time. Others are therefore jumping directly to the largest scales. Thomas Huang, a data scientist at NASA's Jet Propulsion Laboratory, is building a digital twin of the planet's climate. His goal is to use real-time data to improve predictions of how global warming will affect the weather.

His biggest challenge, though, is not finding the data: this exists, often in very high quality, covering everything from temperature records to predictions of how rainfall will change over time. The real difficulty is connecting everything. Even adding something as apparently straightforward as surface temperature measurements relies on integrating information in a range of formats originating from sensors on satellites, ground stations and floats bobbing atop the deep ocean.

It is perhaps when scientists are in full control of the data that digital twins can be most useful. Nowhere is this control more absolute than during the design of large-scale experiments. CERN, for example, runs virtual simulations of how the Large Hadron Collider, a massive particle-smasher, collects data, and uses them to test how small alterations can increase its efficiency. And a digital twin of the orbiting James Webb Space Telescope, perhaps the most complex instrument of its kind ever built, helps scientists on the ground plan changes and maintenance.

In all these cases, the twin not only produces real-time predictions, but relies on a stream of real-world data to keep its predictions relevant. Such two-way modelling helps science itself proceed much faster, says David Wagg, an expert on digital twins at the Alan Turing Institute in London. With a plugged-in virtual twin, forecasts can be tested—and updated—all the time. With so much to recommend them, digital twins are likely to become ever more integral to how science is done. ■



Digital twins (3)

Smart moves

SAN FRANCISCO AND SEATTLE

Corporate twins will make it easier for firms to feel the benefits of AI

WHEN A PASSENGER in search of a taxi orders an Uber, all it takes is a few taps on a smartphone to make a car appear, as if by magic. Traffic permitting, they are soon whisked to their final destination. But the magic tricks do not end there. As soon as that screen is pressed, the passenger—along with all of Uber's other riders, drivers and the systems that connect them—becomes part of a comprehensive digital replica of the firm's inner workings.

This digital twin, one of the most sophisticated of its kind, allows Uber to adjust its operations in real time. Annoyed passengers may think that this enables the firm's "surge pricing", when fares suddenly spike to balance ride demand and driver supply. This is partly true. But the more immediate and more positive effect is that the digital twin allows for up-to-the-minute route optimisations through ever-changing city traffic.

If current technology trends hold, such end-to-end digital representations of a company's inner workings—and, increasingly, its ecosystem of customers and suppliers—will no longer be the speciality of tech firms such as Uber. Artificial intelligence (AI), in particular, will make it much easier for all sorts of businesses to build virtual replicas and oversee them on a scale managers alone never could.

As a result, digital twins will redefine what it means to run a company. Instead of co-ordinating disparate islands of automation, as is the case today, bosses will manage a constantly churning "flywheel" fuelled by data. With access to information from all over the company's operations, as well as from its customers and suppliers, a corporate twin will not just help managers make better plans. It will also implement them, learn from the outcomes and optimise itself to achieve certain corporate objectives—over and over again.

Companies have long tried to model and automate key parts of their business. Even before the global financial crisis hit in 2007, Goldman Sachs, a bank, built a system called SecDB which, among other things, regularly calculated the different types of risk facing its different financial assets. When Lehman Brothers, another bank, went bankrupt in 2008, this system allowed Goldman quickly to understand its exposure to the failing firm.

As such systems multiply and interconnect, companies are in effect building digital twins of themselves—equivalent to recreating a human one organ at a time. What distinguishes these models from their predecessors is their ability to continuously monitor (and influence) their real-world equivalents. Amazon, a big online retailer, is considered to have pushed this process the furthest. After dominating e-commerce for nearly 20 years, the company has amassed vast amounts of sales data, enabling it to build a single model that can forecast demand for 400m items two years into the future. It can even anticipate how a new book by a famous author such as Michelle Obama will fare and how a Taylor Swift concert will impact local demand.

But this model is only part of Amazon's supply-chain optimisation. "Once we have a reliably accurate sales forecast, we can use this as the basis for all planning," explains Ping Xu, who leads forecasting. She oversees a "gym" in which models that optimise different parts of Amazon's supply chain—from how many of a certain item to keep in stock to where to build new warehouses—train together to learn how to act as one coherent model.

What took Amazon years to put together is now becoming much easier to build. Cloud-based databases have helped, allowing companies to store their data in one place for large-scale analysis. So have data-harmonisation techniques, designed to ensure different bits of information are mutually compatible. Molham Aref, the founder of RelationalAI, a startup, aims to turn business processes into what he calls "Lego blocks of digital twins" that can together produce a replica of any company.

The greatest impact on the development of corporate digital twins, however, will come from AI and machine learning. For one, these tools make it easier to grasp the internal processes in need of modelling. Celonis, another startup, currently designs software that trawls a company's internal data for useful insights. In due course AI will be able to perform this discovery process more flexibly and with minimal prior instruction. Just as large language models (LLMs), which power services like ChatGPT, can extract patterns from vast amounts of text, corporate models fed on business data could discover what makes a firm tick, predicts Dario Gil, head of research at IBM.

LLMs will also allow digital twins to adapt. Enterprise software used to involve rigid rules, which made finding workarounds tricky. If a customer wanted to return a product, for example, that would have to be handled in the software-approved manner. Large Action Models, as some call such LLMs, could change that. Trained on complaint messages and other unstructured data, they may be able to offer customer-support workers flexibility, or even perform tasks themselves. "Enterprise software will become more generated-on-demand and self-assembled," says Charles Lamanna, who leads the development of such software at Microsoft.

On the double

Most important, however, AI and digital twins will each enable the other to flourish. Just as fragmented computer systems hamper data analysis, they also constrain what task-performing algorithms known as agents can do. Digital twins offer, in effect, a level playing-field for agents to move on. Such tools will only become more important as agents become easier to build.

What's more, as AI becomes better at capturing what happens inside companies, an ever-bigger part of their internal processes could be turned into software. This could launch a virtuous virtual cycle, in which new enterprise software generates more data, enabling yet deeper AI insights and creating an ever-more detailed digital twin. Firms that jump on such a bandwagon early may well have a lasting advantage.

Such companies are also likely to shift shape. The past 25 years saw the rise of huge tech platforms, including Uber, Google and Meta, most of which are marketplaces that match consumers with goods, services and content. As non-tech businesses, from carmakers to insurers, become more and more embodied in software, they will turn into large platforms. By embracing their digital twins, companies will be able to do more than just match buyers and sellers, orchestrating complex relationships between them too.

If businesses can increasingly be digitally replicated, why stop there? Some firms have started to build digital twins of entire sectors of the economy. J.D. Power, a data-analytics firm, is gathering reams of data on the American automobile industry—including information about individual cars, which dealers stock them, how they are configured, and so on—and how such factors influence sales. With the help of Palantir, a software-maker, J.D. Power is now developing a system that can indicate the current state of the market, as well as show carmakers what is likely to happen if they adjust certain variables, such as increasing incentives in a specific market or supplying more vehicles with luxury packages or in particular colours.

Such opportunities also come with risks. As businesses become ever more reliant on digital twins fed on their most sensitive information, they also leave themselves more vulnerable to being hacked. A well-targeted attack could, in theory, not only grant rogue actors access to a company's deepest secrets, but also allow such data to be secretly manipulated—with real-world consequences. This is magic to be handled carefully. ■